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(54) **HELMHOLTZ TYPE DIFFERENTIAL ACOUSTIC RESONATOR DETECTION DEVICE**

(71) Applicant: **Commissariat A L'Energie Atomique et aux Energies Alternatives**, Paris (FR)

(72) Inventors: **Alain Gliere**, Grenoble (FR); **Salim Boutami**, Grenoble (FR); **Mickael Brun**, Eybens (FR); **Pierre Labeye**, Grenoble (FR); **Sergio Nicoletti**, Sinard (FR); **Justin Rouxel**, Saint-Martin-d'Heres (FR)

(73) Assignee: **Commissariat a l'energie atomique et aux energies alternatives**, Paris (FR)

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USPC 356/437
See application file for complete search history.

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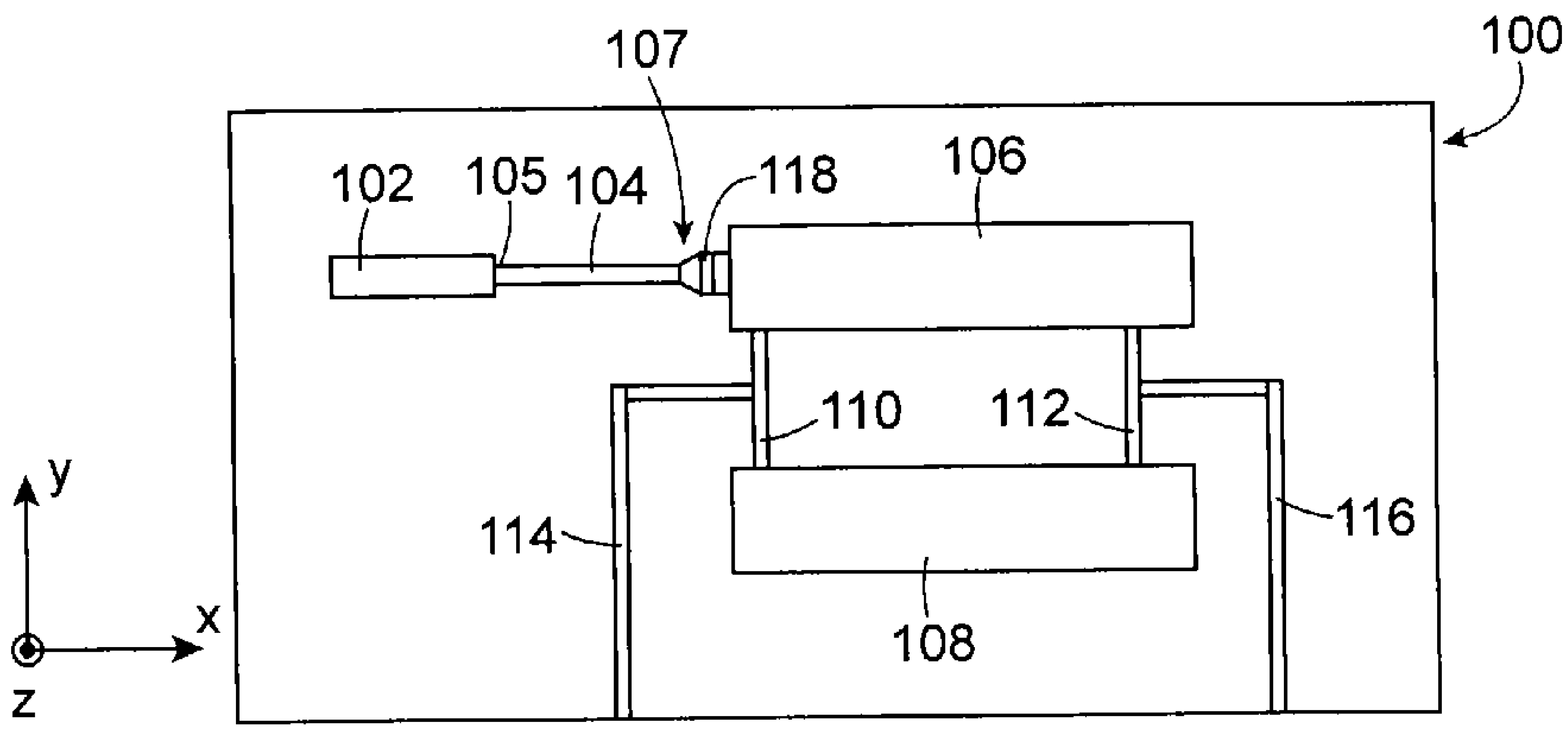
Primary Examiner — Roy M Punnoose
(74) *Attorney, Agent, or Firm* — Oblon, McClelland, Maier & Neustadt, L.L.P.

(57) **ABSTRACT**

Microelectronic photoacoustic detection device comprising:
- a substrate comprising cavities forming a Helmholtz differential acoustic resonator;
- acoustic detectors coupled to the chambers of the resonator;
- a light source;
- a waveguide comprising a first end coupled to the light source and a second end coupled to a first chamber;
- in which the second end comprises, at the interface with the first chamber, a width greater than that of the first end and that of the given wavelength, and/or in which the device comprises a diffraction grating arranged in the second end and capable of diffracting a first part of the beam towards a lower reflective layer arranged under the second end and a second part of the beam towards an upper reflective layer arranged at an upper wall of the first chamber.

14 Claims, 4 Drawing Sheets



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H01S 5/026 (2006.01)
G01N 29/036 (2006.01)
G01N 29/22 (2006.01)
G01N 29/24 (2006.01)
G01N 21/17 (2006.01)

(52) **U.S. Cl.**

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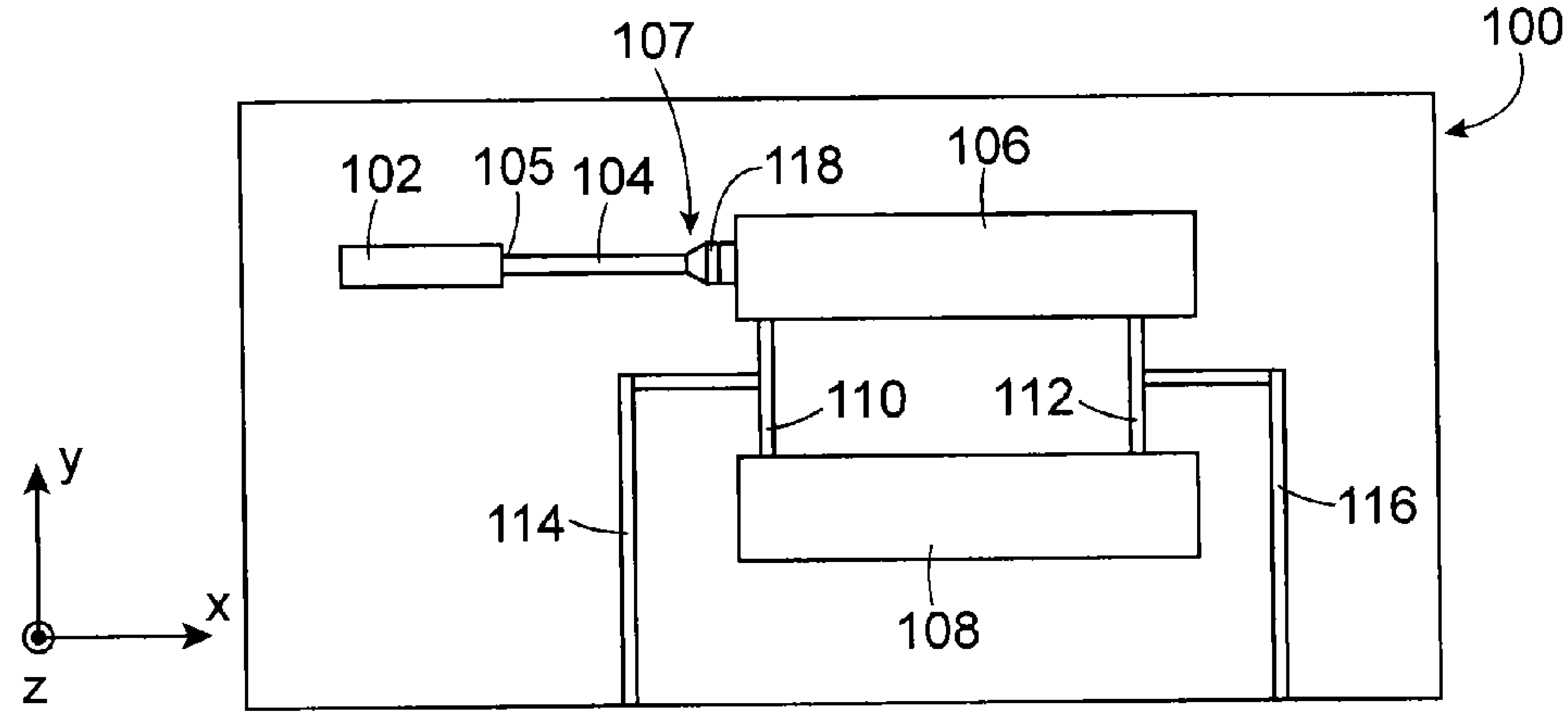


FIG.1

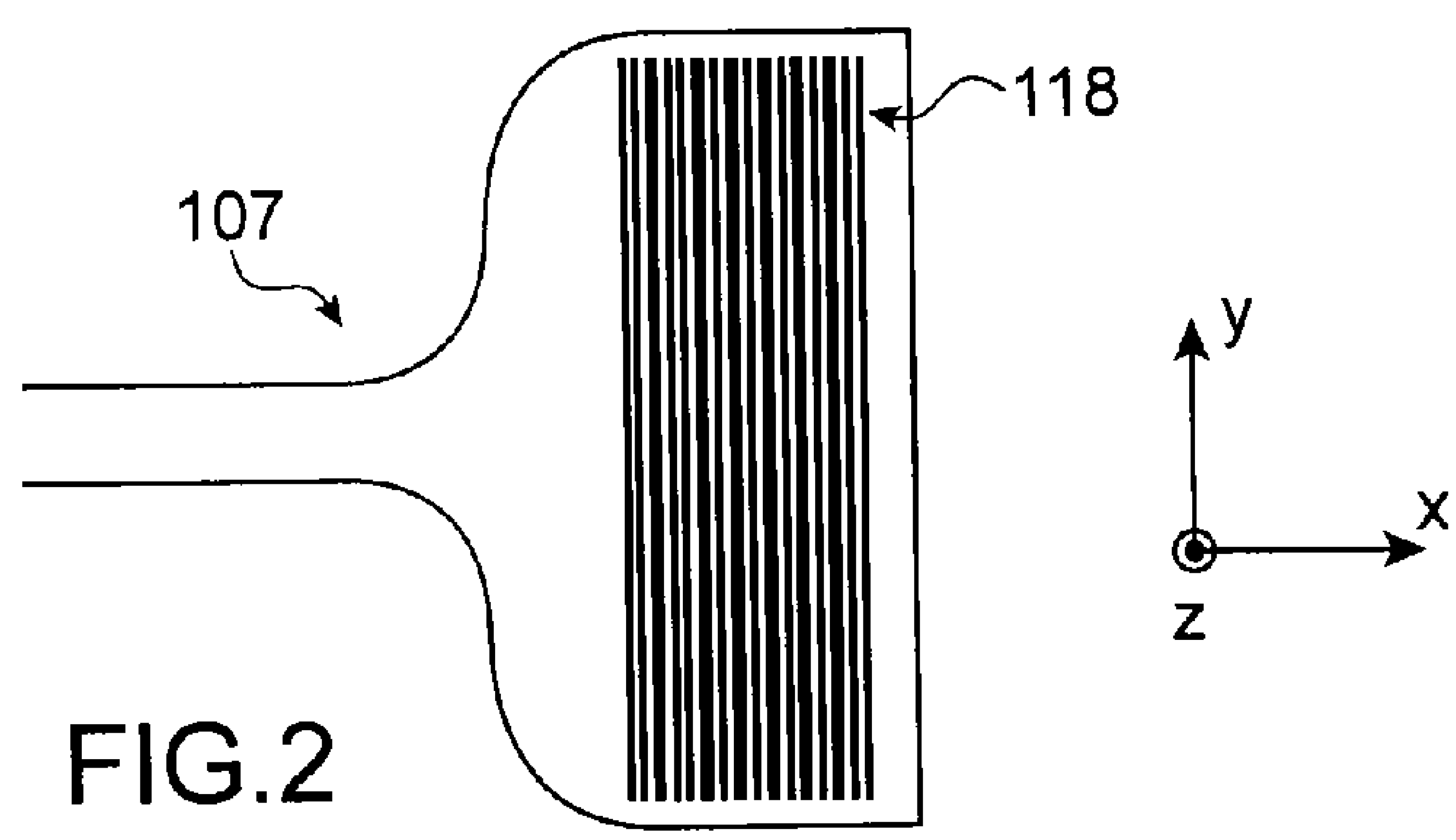


FIG.2

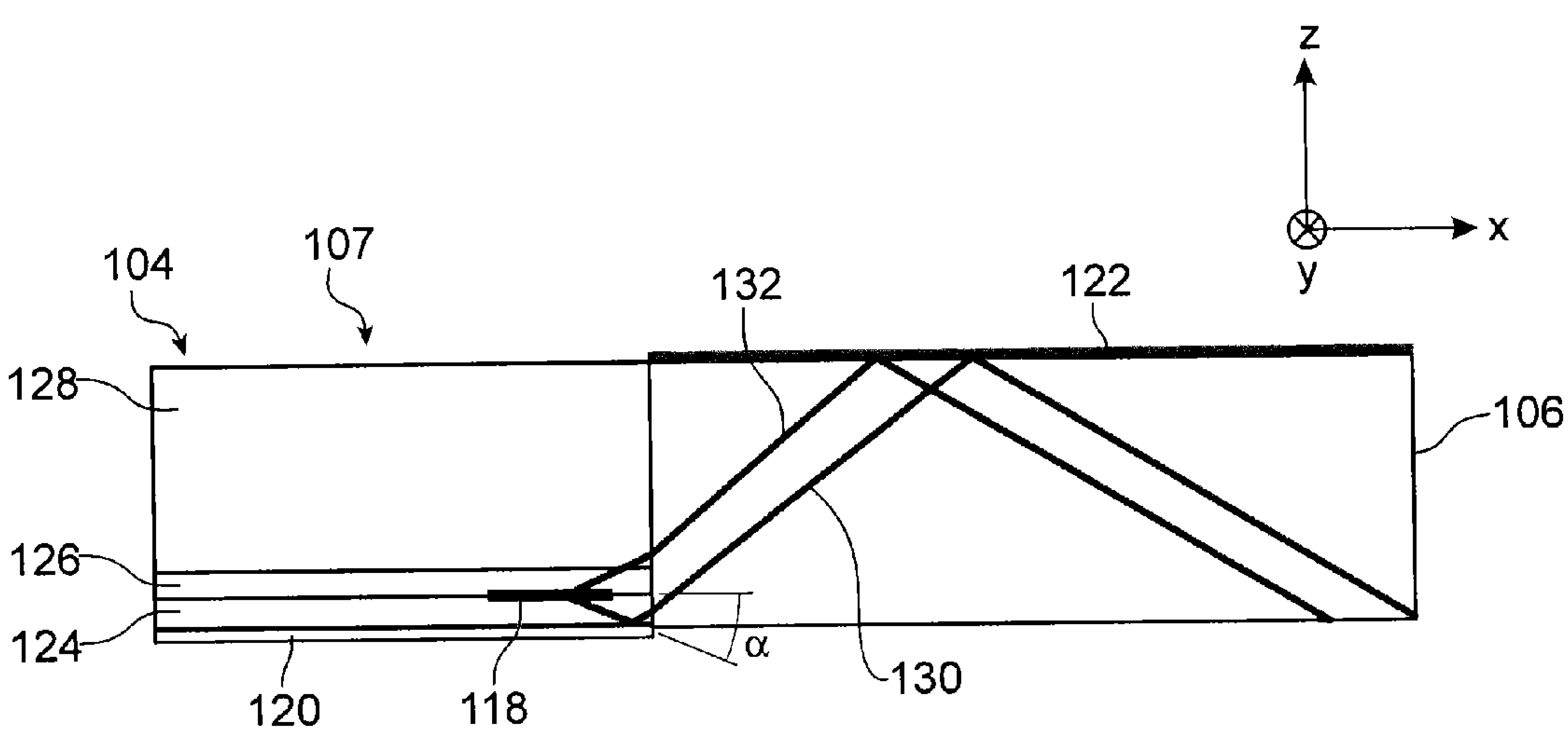
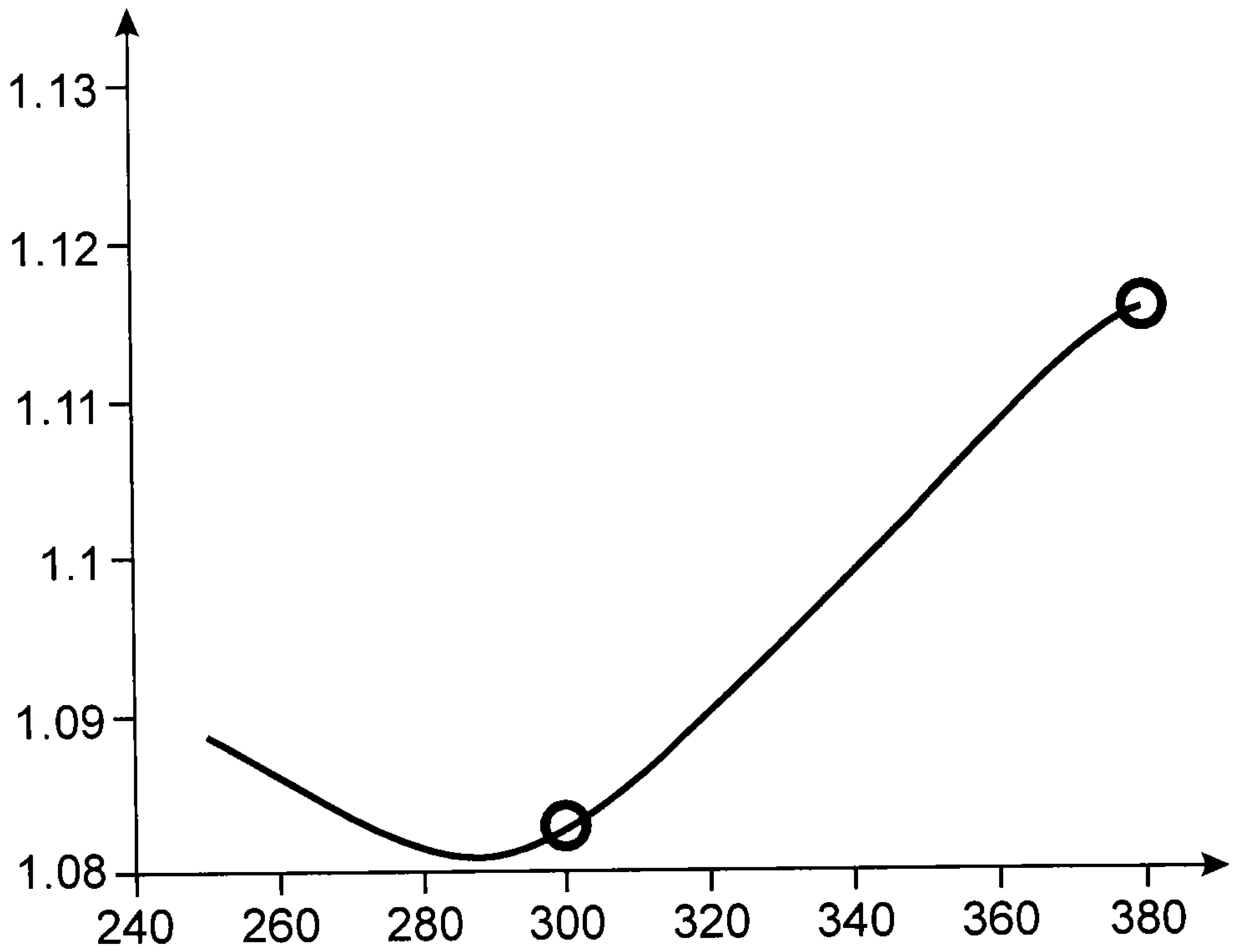


FIG.3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1.12
1.11
1.1
1.09
1.08
240
260
280
300
320
340
360
380

FIG.4

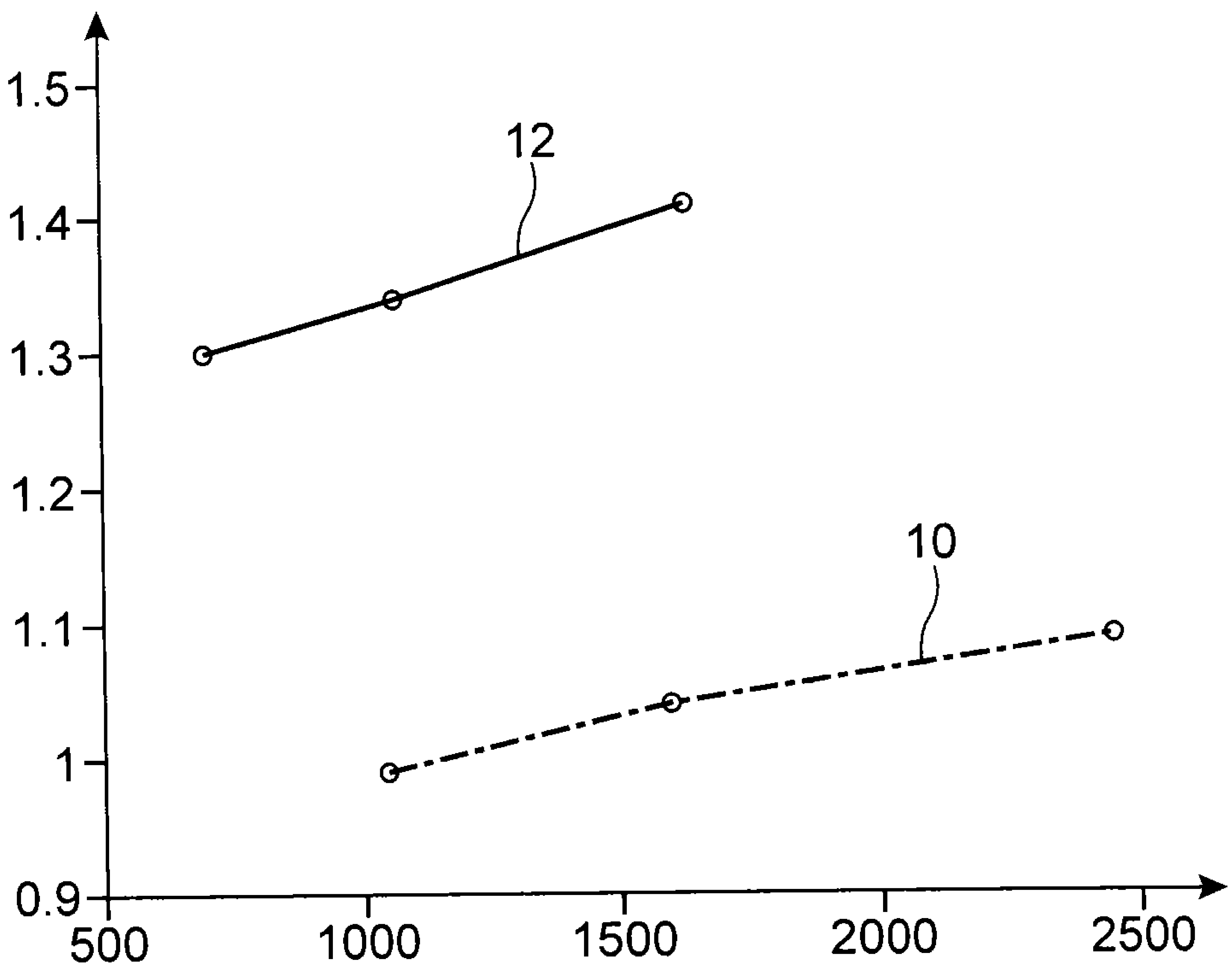
1.5
1.4
1.3
1.2
1.1
1
0.9
500
1000
1500
2000
2500
12
10

FIG.5

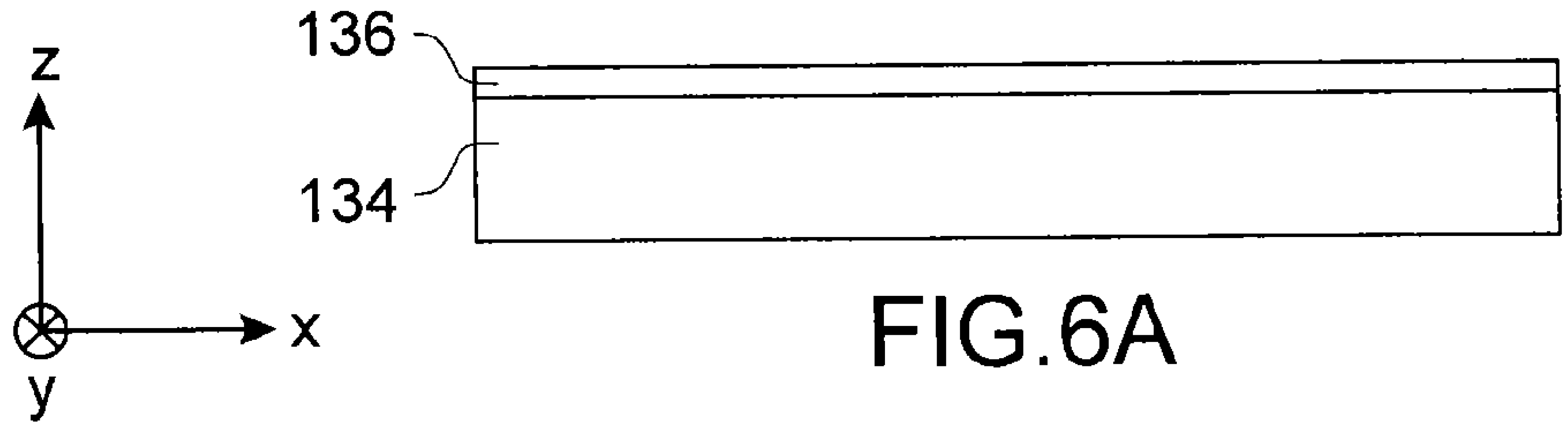

FIG.6A

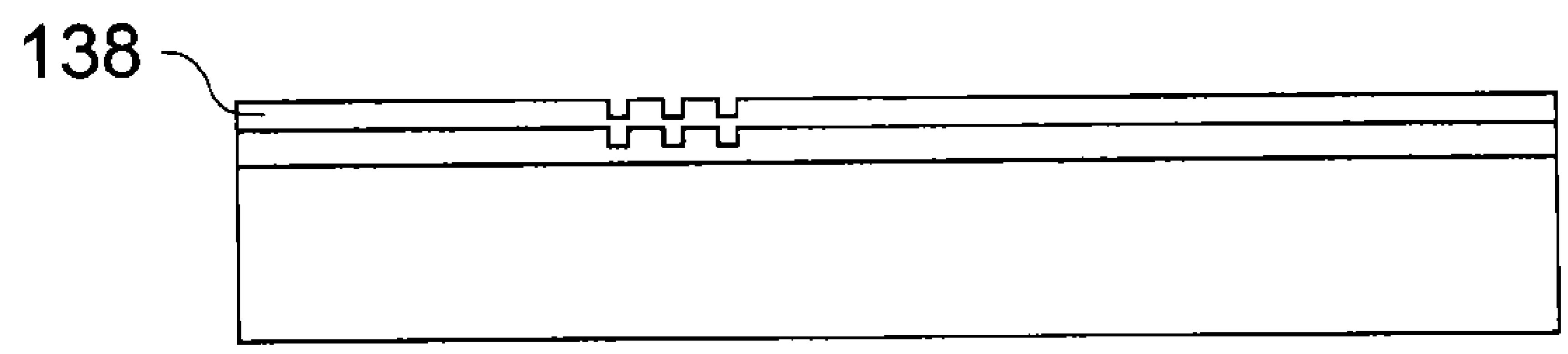

FIG.6B

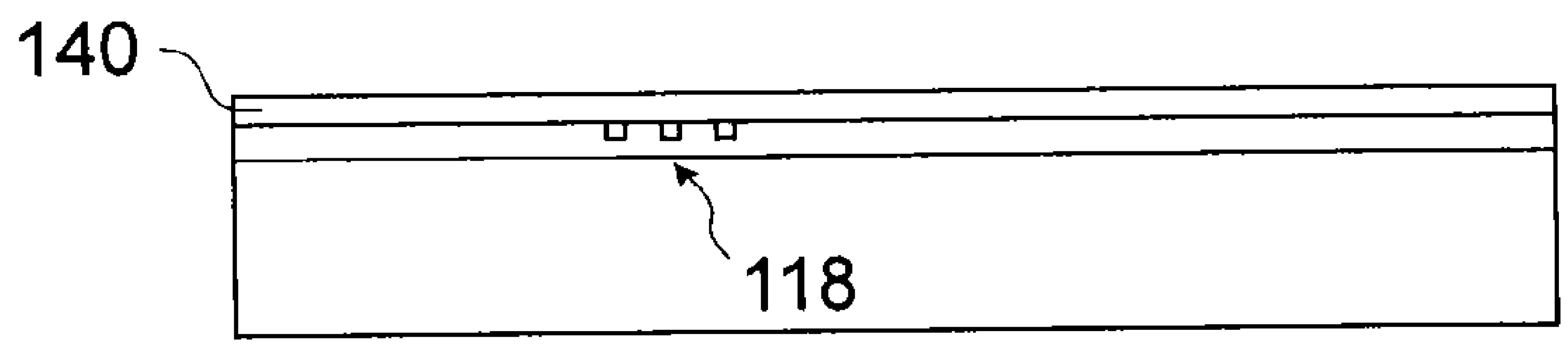

FIG.6C

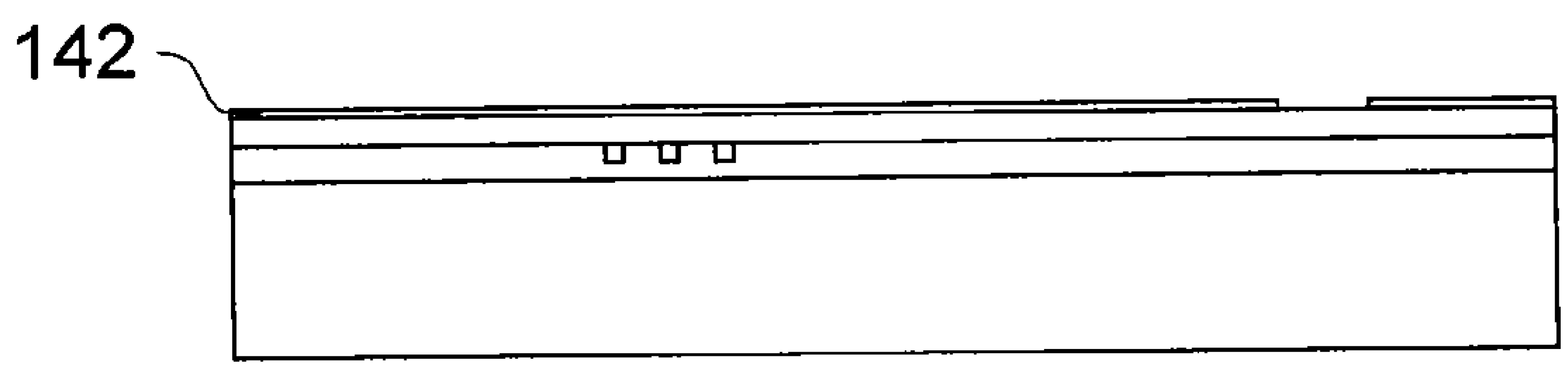

FIG.6D

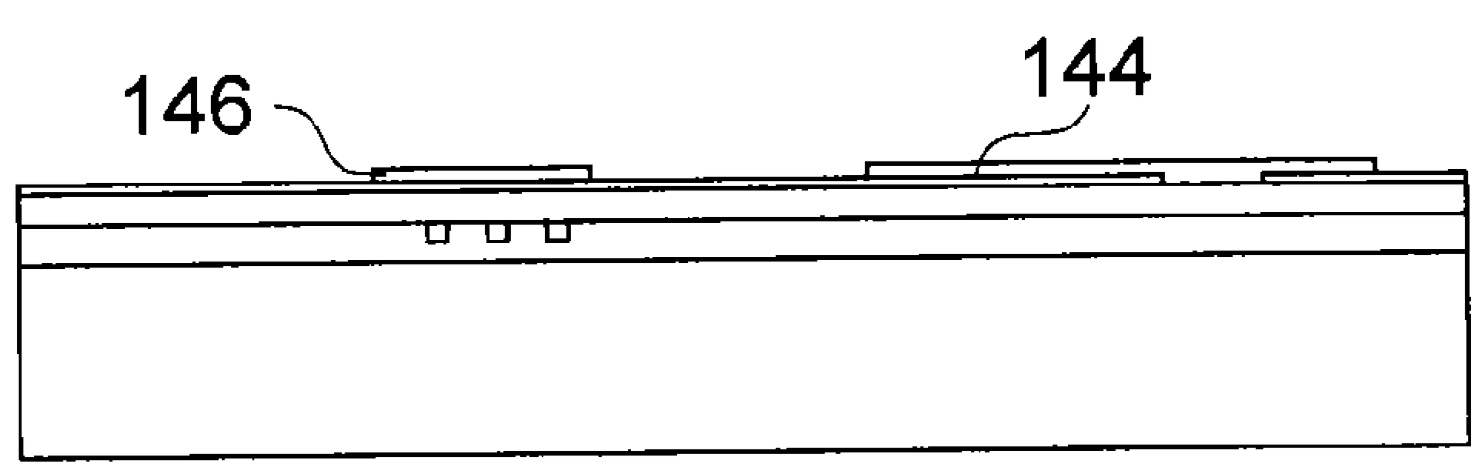

FIG.6E

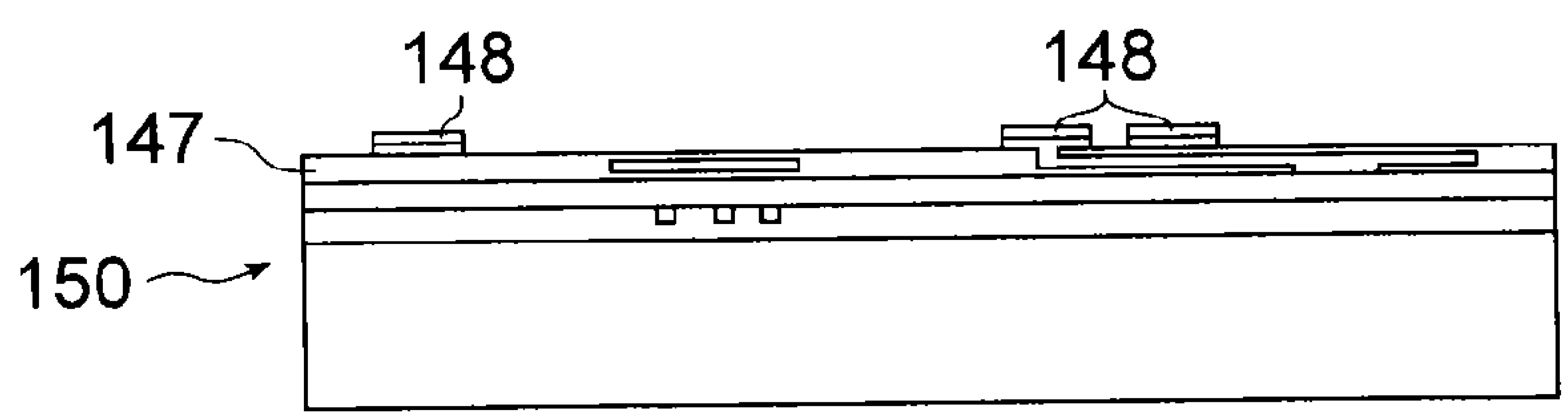

FIG.6F

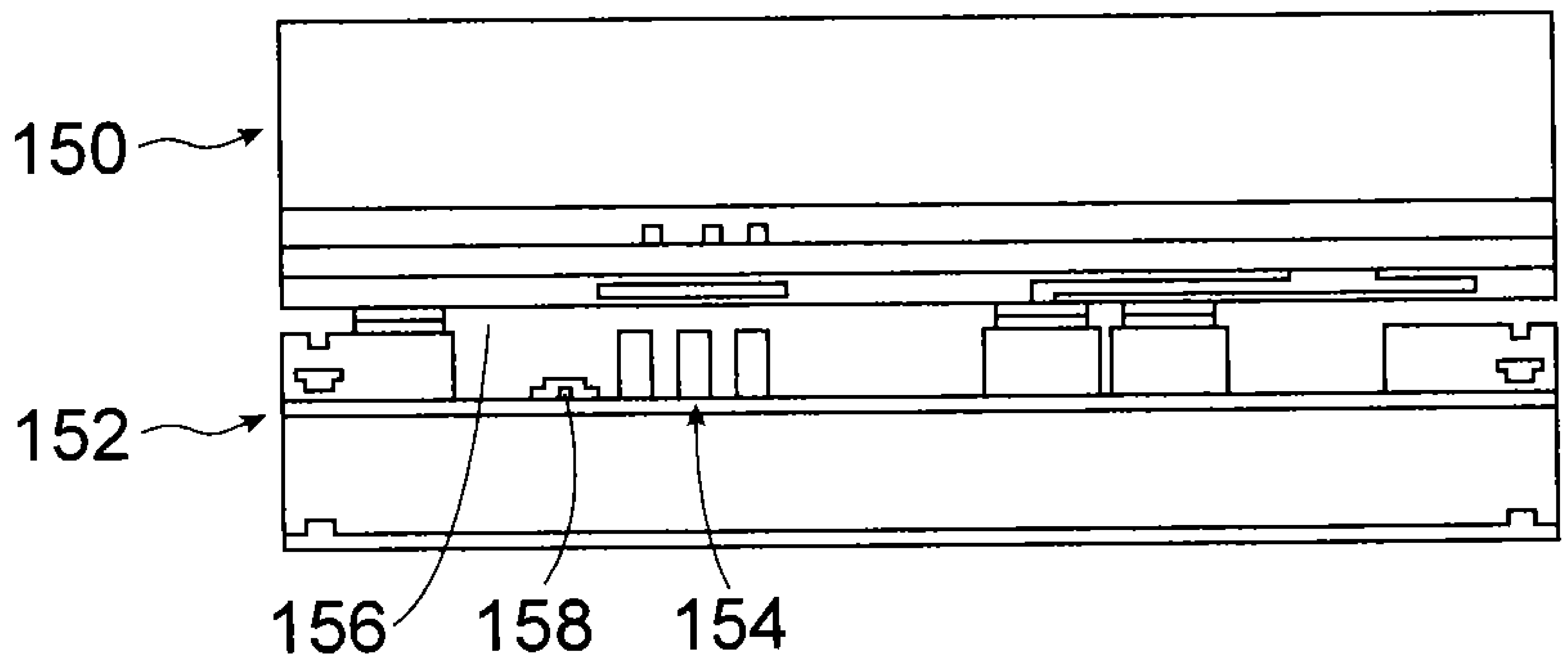

FIG.6G

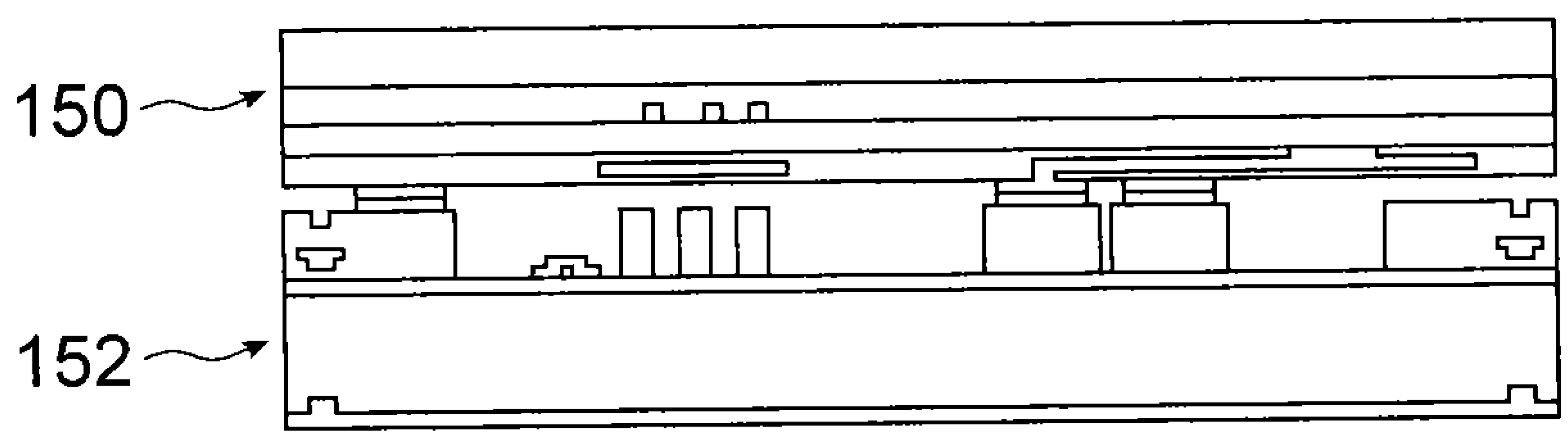

FIG.6H

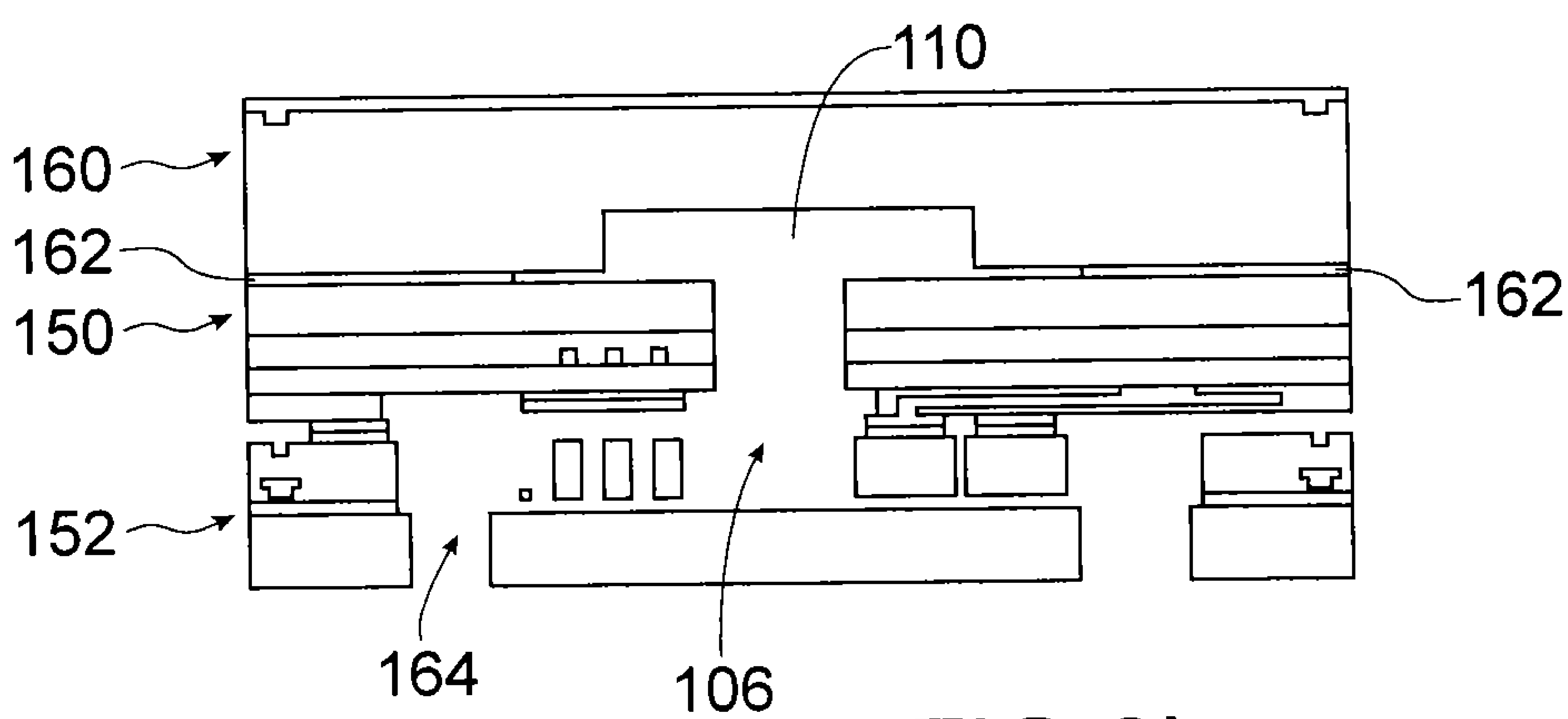

FIG.6I

HELMHOLTZ TYPE DIFFERENTIAL ACOUSTIC RESONATOR DETECTION DEVICE

TECHNICAL FIELD AND PRIOR ART

The invention relates to the field of photoacoustic detection devices, and especially that of integrated gas sensors making use of a photoacoustic effect to measure the concentration of some gaseous elements.

The principle of measuring a gas by photoacoustic effect is based on the excitation of an acoustic wave in the gas by a powerful light source such as a pulsed or amplitude or wavelength modulated laser. The wavelength of the mid-infrared radiation (MIR) emitted by the laser is chosen to interact with the molecules of the gas to be detected. Since the emission of the light source is variable over time, the energy absorbed by the gaseous molecules is restored in the form of a transitory heating which generates a pressure wave, itself measured by an acoustic detector.

Detection is improved by confining the gas in a cavity and by modulating the laser to an acoustic resonance frequency of the cavity. The amplitude of the acoustic wave obtained is directly linked to the concentration of the gaseous compound searched for in the gas present in the excited cavity.

The detection efficiency is based to a large extent on the efficient coupling of the luminous flux coming from the laser with the gas contained in the resonant cavity because the signal measured is proportional to the energy absorbed, then dissipated, by the gas.

The document WO 03/083455 A1 describes a photoacoustic measurement device which makes it possible to detect the presence of a gas and comprising a particular structure of photoacoustic cells designated "Differential Helmholtz Resonator" (DHR), or Helmholtz type differential acoustic resonator. Such a resonator comprises two identical chambers connected together by two capillaries.

Acoustic resonance is produced by exciting only one of the two chambers. At resonance, the pressures in the two chambers oscillate in phase opposition. The pressures in the chambers are measured by microphones placed in the two chambers. With such a resonator, the calculation of the difference between the signals coming from each chamber, which corresponds to the useful signal, makes it possible to increase the amplitude of the measured signal and to eliminate part of the surrounding noise, and thus to have in the end a good signal to noise ratio. Another type of differential photoacoustic resonator is described in the document WO 2008/074442 A1.

Such devices nevertheless have the drawbacks of being limited to non-miniaturised laboratory devices, of having limited transmission wavelengths, of being sensitive to temperature variations and to vibrations, and of having considerable constraints of positioning and alignment of their elements to produce them.

A miniaturisation of such a device at the millimetric scale is proposed in the document U.S. Pat. No. 7,304,732 B1. This miniaturisation makes it possible to have a stronger pressure signal produced by the sensor due to the fact that said signal increases when the size of the resonator is reduced. DHR resonators are particularly well suited to miniaturisation and integration on silicon because they are relatively insensitive to the localisation of the thermal energy deposition and because, the pressure being virtually constant in each chamber, it is possible to multiply the number of microphones per chamber to improve the signal to noise ratio.

The document EP 2 515 096 A1 describes a photoacoustic gas detection device comprising a miniaturised photoacoustic

resonator integrated on silicon. The structure of said detector is obtained by the implementation of techniques of the field of microelectronics in several substrates bonded together. The manufacturing process imposes placing the MIR waveguide, which makes it possible to inject the optical laser signal into one of the two chambers, in the lower part of the central substrate which is thinned to a thickness determined by the height of the chambers.

The miniaturisation and the integration on silicon of this type of detector nevertheless pose a problem. In fact, the MIR produced by the laser is transmitted up to the chamber excited by a waveguide of section comparable to the wavelength of the radiation. At the inlet of the excited chamber, the beam undergoes a diffraction due especially to the low thickness of the silicon, which leads to a significant divergence of the beam. This divergence of the light beam, allied to the transparency of the silicon (in which is the resonator is manufactured), leads to poor confinement of the light and thus to poor light-gas coupling. This phenomenon is exacerbated by the fact that the luminous flux penetrates near to the bottom of the chamber. Furthermore, this poor confinement may lead to partial illumination of the second chamber (phenomenon of diaphony), which reduces the amplitude of the useful signal obtained.

DESCRIPTION OF THE INVENTION

Thus there is a need to propose a DHR integrated type of photoacoustic detection device, and in which the confinement of the light beam intended to be injected into one of the chambers of the device is improved.

To achieve this, one embodiment proposes a photoacoustic detection device comprising:

- at least one substrate comprising cavities forming a Helmholtz type differential acoustic resonator (or DHR);
- acoustic detectors coupled to two of said cavities forming chambers of the resonator;
- a light source capable of emitting a light beam at at least one given wavelength;
- an optical waveguide comprising a first end optically coupled to the light source and a second end optically coupled to a first of the two chambers;

in which the second end comprises, at an interface with the first chamber, a width of value greater than that of the width of the first end and greater than that of said at least one given wavelength, and/or in which the photoacoustic detection device comprises at least one diffraction grating arranged in the second end of the waveguide and capable of diffracting a first part of the light beam towards a lower reflective layer arranged under the second end and a second part of the light beam towards an upper reflective layer arranged at an upper wall of the first chamber.

In this photoacoustic detection device, the confinement of the light beam is improved horizontally via the widening of the second end of the waveguide that is optically coupled to the first chamber, which is intended to receive the light beam, due to the fact that said widening makes it possible to reduce or even to cancel the diffraction of the light beam in the direction parallel to said width. The confinement of the light beam is moreover improved vertically thanks to the diffraction grating that makes it possible to diffract the light beam in a specific direction towards the reflective layers, which makes it possible to confine the light beam in the first chamber.

The term "width" is used here and throughout the remainder of the document to designate, with reference to the waveguide, the dimension that lies in a propagation plane of the light beam in the waveguide and which is perpendicular or substantially perpendicular to a direction of propagation of the light beam in the waveguide. More generally, the term "width" designates the dimension which is perpendicular or substantially perpendicular to a direction of propagation of the light beam in the waveguide.

Preferably, the optical waveguide may be such that it operates on the fundamental mode for which the diffraction grating is dimensioned and diffracts at a very precise angle. Such a single mode operation of the optical waveguide is advantageous because it enables better control of the direction of the light beam. If several modes are excited, these modes can diffract in several directions. Nevertheless, in the case of a multimode waveguide, a small index difference between the core and the cladding of the waveguide can make it possible to limit the variation in the effective index of the guide.

Advantageously, the photoacoustic detection device comprises at one and the same time an optical waveguide of which the second end has, at an interface with the first chamber, a width greater than that of the first end and at said given wavelength, and the diffraction grating arranged in the second end of the waveguide and coupled to the lower and upper reflective layers. This configuration makes it possible to improve the horizontal and vertical confinement of the light beam.

The value of the width of the second end is preferably greater than or equal to several times that of said given wavelength.

The "DHR" type detection device is a microelectronic device, that is to say obtained by successive steps of deposition of layers, of etching, and potentially of planarization, implantation and transfer. Such a microelectronic device preferentially occupies, on the substrate, a surface area less than around 25 mm^2.

The lower reflective layer corresponds to the lower reflective layer of the optical waveguide.

The upper wall of the first chamber is formed by the upper reflective layer.

The device functions when the waveguide comprises a second end wider than the first end and that it comprises the diffraction grating arranged in the second end of the waveguide. Nevertheless, the device also operates when the waveguide comprises a second end wider than the first end but that it does not comprise the diffraction grating, or instead when the waveguide does not comprise a second end wider than the first end but that the diffraction grating is arranged in said second end.

The ratio between the width of the second end at the interface with the first chamber and the width of the first end may be greater than or equal to 3.

The second end may form a portion of the waveguide of which the width increases from a first value equal to that of the width of the first end up to a second value equal to that of the width of the second end at the interface with the first chamber.

In this case, the width of the second end may increase on a part, called first part, of the second end of which the length may be greater than or equal to around ten times the width of the second end at the interface with the first chamber. The term "length" here designates, with reference to the waveguide, the dimension that lies in the propagation plane of the light beam in the waveguide and which is parallel to the direction of propagation of the light beam in the waveguide (and thus perpendicular to the width defined previously). The terms "thickness" and "height" refer to the dimension which is perpendicular to the width and to the length. Such a progressive increase in the width of the second end of the waveguide makes it possible to conserve well the single mode character of the transmission of the light beam formed by the waveguide.

The diffraction grating may be arranged in a part, called second part, of the second end of which the width may be substantially constant and equal to that at the interface with the first chamber.

The diffraction grating may be arranged at an interface between a core layer of the waveguide and a lower cladding layer of the waveguide, the lower cladding layer being able to be arranged between the core layer and the lower reflective layer.

The diffraction grating may be capable of diffracting the light beam such that the first or the second part of the light beam reaches, after a reflection on the lower reflective layer and/or the upper reflective layer, a bottom wall of the first chamber which is opposite to that in contact with the second end of the waveguide. Thus, the diffraction grating may be dimensioned, especially as regards the pitch of the grating, such that the path of the light beam is maximised in the first chamber for the first or the second part of the light beam. Although this configuration is advantageous, it is entirely possible that the diffraction grating is not dimensioned so that the first or the second part of the light beam reaches, after a reflection on the lower reflective layer and/or the upper reflective layer, the bottom wall of the first chamber.

The acoustic detectors may be arranged in a first substrate and be coupled to the chambers of the resonator formed in a second substrate made integral with the first substrate, volumes of the chambers being able to communicate together via capillaries formed in a third substrate made integral with the second substrate.

In a variant, the acoustic detector may be arranged in a first substrate and be coupled to the chambers of the resonator formed in a second substrate made integral with the first substrate, volumes of the chambers communicating together via capillaries formed in the second substrate, the second substrate having a thickness less than 300 μm. Thus, by forming the capillaries and the chambers in a same substrate, it is possible to reduce the thickness of the chambers, and potentially that of the capillaries, to a value less than 300 μm.

The device may further comprise trenches filled with at least one optically reflective material and arranged around the first chamber, and especially around lateral walls of the first chamber. Such trenches contribute to improving the horizontal confinement (that is to say in the direction parallel to the width of the waveguide) of the light beam.

The two chambers may comprise dimensions different to each other. Such asymmetry of said chambers can make it possible to optimise the phase opposition of the acoustic signals measured in the two chambers.

The acoustic detectors may comprise beam type piezoresistive microphones.

Another embodiment relates to a gas detection device, comprising at least one photoacoustic detection device as described previously and further comprising gas inlet and outlet channels communicating with the chambers of the resonator, for example through the intermediary of capillaries, and in which the wavelength intended to be emitted by the light source corresponds to an absorption wavelength of a gas intended to be detected. Such a device thus forms a low cost gas sensor being able to be used for example in the field of gas detection outside (detection of pollution, measurement of greenhouse gas effect, etc.) or inside (interior air quality, air conditioning, detection of substances in an interior space, etc.).

Another embodiment relates to a method of producing a photoacoustic detection device, comprising at least the steps of:

forming, in at least one substrate, an optical waveguide comprising a first end and a second end,

forming a light source capable of emitting a light beam at at least one given wavelength and such that the light source is optically coupled to the first end of the waveguide,

forming, in said at least one substrate, cavities forming a Helmholtz type differential acoustic resonator, two of said cavities forming chambers of the resonator such that a first of the two chambers is optically coupled with the second end of the waveguide,

coupling acoustic detectors with the chambers of the resonator,

in which the second end comprises, at an interface with the first chamber, a width of value greater than that of the width of the first end and greater than that of said at least one given wavelength, and/or in which the method comprises the formation of at least one diffraction grating in the second end of the waveguide capable of diffracting a first part of the light beam towards a lower reflective layer arranged under the second end and a second part of the light beam towards an upper reflective layer arranged at an upper wall of the first chamber.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will be better understood on reading the description of embodiment examples given for purely illustrative purposes and in no way limiting and by referring to the appended drawings in which:

FIG. **1** schematically represents a photoacoustic detection device according to a particular embodiment,

FIG. **2** schematically represents an embodiment example of a second end of the waveguide of the photoacoustic detection device,

FIG. **3** schematically represents a part of the photoacoustic detection device,

FIG. **4** represents the amplitude of the signal measured by the gas detection device as a function of the difference between the widths of the chambers of the device,

FIG. **5** represents the amplitude of the signal measured by the gas detection device for different distances between the capillaries and for chambers of different dimensions,

FIGS. **6**A to **6**I represent the steps of a method of producing a photoacoustic detection device,

Identical, similar or equivalent parts of the different figures described hereafter bear the same numerical references so as to make it easier to go from one figure to the next.

The different parts represented in the figures are not necessarily according to a uniform scale in order to make the figures more legible.

The different possibilities (variants and embodiments) must be understood as not being exclusive of each other and may be combined together.

DETAILED DESCRIPTION OF PARTICULAR EMBODIMENTS

Reference will firstly be made to FIG. **1** which schematically represents a photoacoustic detection device **100** according to a particular embodiment. This photoacoustic detection device **100** corresponds to a gas detection device.

The device **100** comprises a powerful light source **102**, here corresponding to a laser. This laser may correspond to a laser of QCL (quantum cascade laser) type emitting in the MIR field, for example at wavelengths comprised between around 3 μm and 10 μm. Although not represented, the device **100** also comprises an electrical supply of the light source **102** as well as means of modulating the light beam emitted to an acoustic resonance frequency of the cavity into which the beam is intended to be sent. Compared to the use of a light source **102** which would not be collimated, the use of a collimated light source **102** in the device **100** makes it possible to considerably increase the signal/noise factor, for example by a factor **2**. The window noise corresponds to the parasitic acoustic signal that all solid parts emit when they are struck by the modulated light wave.

The light beam emitted is then transmitted into an optical waveguide **104**, advantageously single mode and for example formed of a Si/Ge/Si stack, or SiN/Si/SiN stack, or more generally a stack of a first material of optical index n_1, of a second material of optical index $n_2>n_1$, and of a third material of optical index $n_3<n_2$ (with n_3 potentially equal to n_1), these three materials being transparent to the wavelength emitted by the light source **102**. The optical waveguide **104** comprises a first end **105** optically coupled to the light source **102**. The coupling between the light source **102** and the waveguide **104** may be carried out directly, for example by evanescent waves, or via the use of a coupler (not represented in FIG. **1**) for example of taper type (forming an extruded elongated trapeze).

The device **100** also comprises elements corresponding to cavities, or hollowings out, formed in one or more substrates integral with each other, and forming a Helmholtz type differential acoustic resonator (DHR). These elements are:

a first chamber **106** in which the gas to be detected is intended to be excited by the light beam emitted by the source **102**, and of which an inlet face intended to receive the light beam is optically coupled to a second end **107** of the waveguide **104**;

a second chamber **108**;

two capillaries **110** and **112** enabling the volumes of the chambers **106** and **108** to communicate together.

The device **100** also comprises an inlet channel **114** making it possible to feed the gas into the chambers **106** and **108** via the capillary **110**, and an outlet channel **116** making it possible to evacuate the gas outside of the chambers **106** and **108** via the capillary **112**. In FIG. **1**, the inlet **114** and outlet **116** channels are connected to the capillaries **110** and **112** substantially at the level of the middle of said capillaries **110**, **112**. Acoustic detectors (not visible in FIG. **1**) such as miniaturised piezoresistive microphones, for example of membrane or beam type, are also coupled to the chambers **106**, **108** in order to carry out pressure measurements in the chambers **106**, **108**. Each of the chambers **106**, **108** may be coupled to one or more microphones, for example up to eight microphones per chamber. Finally, the device **100** also comprises electronic circuits for processing the signals delivered by the acoustic detectors which are not represented in FIG. **1**.

The operating principle of the device **100** is similar to that described in the document EP 2 515 096 A1 and is thus not described in detail herein.

In order to confine the light beam in the first chamber **106** and thus to improve the light-gas coupling occurring in the first chamber **106**, the device **100** comprises an element making it possible to control the horizontal divergence (along the y axis represented in FIG. **1**) of the light beam at the interface between the first chamber **106** and the second end **107** of the waveguide **104**, and an element making it possible to control the vertical divergence (along the z axis represented in FIG. **1**) of the light beam at said interface.

Thus, at the interface with the first chamber **106**, the second end **107** of the waveguide **104** is formed such that its width (dimension along the y axis), that is to say its dimension situated in the propagation plane of the light beam and which is perpendicular to the direction of propagation of the light beam, increases in order to achieve the horizontal confinement of the light beam due to the fact that this increase in the width of the second end **107** of the waveguide **104** leads to a reduction in diffraction in the direction of said widening. This widening of the second end **107** of the waveguide **104** is represented schematically in FIG. **2** that represents a top view of the waveguide **104** at its second end **107** which is located at the interface with the first chamber **106**. This widening of the second end **107** of the waveguide **104** is progressive and preferably such that it conserves the single mode character of the transmission of the light beam up into the first chamber **106**. Such a widening may be qualified as adiabatic when the effective index varies linearly and when it makes it possible to conserve the single mode character while minimising the length of said second end **107**. The second end **107** of the waveguide **104** may for example have an initial width, equal to that of the remainder of the waveguide **104** and especially equal to that at the first end **105**, equal to around 3 μm, or comprised between around 3 μm and 8 μm, and a final width (width at the interface with the first chamber **106**) equal to around 30 μm, or comprised between around 30 μm and 40 μm or between around 30 μm and 50 μm, that is to say here a ratio between the final width and the initial width comprised between around 10 and 13.33. The ratio between the final width and the initial width is for example comprised between around 3 and 20, and for example around 10. In order to conserve the single mode character of the transmission of the light beam up to the chamber **106**, this widening is for example made over a length of around 300 μm, or comprised between around 50 μm and 500 μm. The value of the initial width may be of the order of that of the wavelength of the light beam emitted to achieve a single-mode guiding of said light beam, and the value of the final width is greater than that of said wavelength to obtain a horizontal confinement of the light beam.

The control of the vertical divergence of the light beam is carried out thanks to a diffraction grating **118** formed at the second end **107** of the waveguide **104**, and more particularly at a part of this second end **107** of which the width is substantially constant and equal to that at the interface with the first chamber **106**. This control of the vertical divergence of the light beam is also achieved thanks to a lower reflective layer **120** arranged under the second end **107** and extending up to the level of the inlet face of the first chamber **106**, and thanks to an upper reflective layer **122** arranged at the upper wall of the chamber **106**. The diffraction grating **118** comprises a series of parallel grooves, or slits, formed in the core layer of the waveguide **104** (which is for example germanium-based), the grooves being filled with a material of which the refractive index is less than that of the material of the core layer, for example with SiO_2, silicon nitride, etc. The diffraction grating **118** is for example formed over a length of around 1 mm to obtain a sufficient decoupling efficiency of the order of 60%.

FIG. **3** represents the second end **107** of the waveguide **104** formed by a first silicon layer **124**, on which is arranged a core layer **126**, for example made of germanium, itself covered by a second layer **128** of silicon, the layers **124** and **128** forming the upper and lower cladding layers of the waveguide **104**. In a variant, the core layer **126** could be made of silicon, and the layers **124** and **128** made of SiN. The diffraction grating **118** is preferably formed at the lower part of the core layer **126** which is in contact with the lower cladding layer **124** in order to avoid, while the diffraction grating **118** is being formed, the implementation of an epitaxy of the core material on a non-flat silicon layer. Nevertheless, it is possible that the diffraction grating **118** is formed at the upper part of the core layer **126** which is in contact with the upper cladding layer **128**. In the configuration represented in FIG. **3**, one or more acoustic detectors (not represented in this figure) are coupled to the first chamber **106**, at the lower wall of the chamber **106**, and to the second chamber **108**.

A first part **130** of the light rays diffracted by the diffraction grating **118** are oriented downwards, that is to say towards the lower reflective layer **120**, and a second part **132** of the light rays diffracted by the diffraction grating **118** are oriented upwards, that is to say towards the upper reflective layer **122**. The pitch of the diffraction grating **118** is calculated so that the diffraction angle of the rays **130** and **132** (said angle being the same for the rays **130** and **132**) is such that the rays **130** oriented downwards or the rays **132** oriented upwards pass through the whole length of the first chamber **106**, which is for example around 2.6 mm, in order to maximise the path length of the light radiation in the first chamber **106**. In the example represented in FIG. **3**, this diffraction angle is such that the rays **130**, which reflect firstly on the lower reflective layer **120**, pass through the whole length of the first chamber **106**, said passing through of the first chamber **106** being realised with a reflection on the upper reflective layer **122** in order to maximise the path length in the first chamber **106**. In a variant, the diffraction grating **118** could be such that the diffraction angle formed by the rays diffracted by the grating **118** enables the rays **132** to pass through the whole length of the first chamber **106**.

Thanks to the widening of the second end **107** of the waveguide **104** and to the presence of the diffraction grating **118** and the reflective layers **120** and **122**, a confinement of the light rays in the first chamber **106** is obtained, thereby improving the light-gas coupling in the first chamber **106** and also avoiding the second chamber **108** being partially illuminated due to the divergence of the beam.

An example of optical dimensioning of the elements of the device **100** is described below. This example is calculated for a first chamber **106** intended to receive light rays which is of rectangular shape and which comprises a width and a height each equal to around 300 μm, and a length equal to around 2.6 mm. Considering the example described previously with reference to FIG. **3** in which the path of the rays **130** (that is to say the rays diffracted towards the lower reflective layer **120** then towards the upper reflective layer **122**) is maximised, the desired value of the diffraction angle α with which the light rays are diffracted by the diffraction grating **118** is firstly calculated in such a way that said rays pass through the whole length of the chamber **106**. The value of the diffraction angle α (angle measured with respect to the axis of the waveguide **104**) is calculated from the following transcendent equation:

$$\sin(\alpha) = \frac{n_2}{n_1}\sin\left[a\tan\left(\frac{2H - h_0 - d\tan(\alpha)}{d}\right)\right] \qquad (1)$$

with n_2 corresponding to the refractive index in the chamber **106**, that is to say here equal to around 1,

n_1 corresponding to the refractive index of the material of the first layer **124** in which the rays are diffracted, and equal to around 3.4 in the case of a first layer **124** made of silicon,

H the height of the chamber **106**, here equal to 300 μm,

h_0 the thickness of the first layer **124**, here equal to around 10 μm,

d the distance between the centre of the diffraction grating **118** and the inlet face of the chamber **106**, that is to say half the length of the diffraction grating **18**, here equal to around 0.5 mm.

The diffraction angle formed by the other rays (the rays **132** in the example of FIG. **3**) will be similar to that for the rays of which the path is maximised in the first chamber **106**. Nevertheless it is advisable to have a diffraction angle sufficiently small so that these other rays are directed all the same towards the inlet face of the chamber **106**.

The pitch Λ of the diffraction grating **118** is then calculated according to the following equation:

$$\Lambda = \frac{m\lambda}{n_{eff} - n_{Si}\cos\alpha} \quad (2)$$

with m corresponding to the order of diffraction and which is equal to 1 for the calculation of the pitch of the grating,

λ corresponding to the wavelength emitted by the light source **102**,

n_{Si} corresponding to the refractive index of silicon (more generally of the material of the lower layer **124**),

α corresponding to the diffraction angle,

n_{eff} corresponding to the effective index, that is to say the index seen by the mode (at the propagation velocity of the mode in the guide).

The light source **102** emits a laser radiation in the MIR field at a wavelength λ equal to 4 μm. For a diffraction angle equal to 3.7° in silicon and equal to 12.5° in air, a pitch of 39 μm is obtained for $\alpha=4°$, $n_{Si}=3.4$ and $n_{eff}=3.5$. When this diffraction grating **118** is formed over a length of around 1 mm on a waveguide **104** of which the width goes from 3 μm to 30 μm over a length of around 300 μm, an absorption of around 11.1 mW per incident W (power of the beam entering the chamber) in the CO_2 contained in ambient air is obtained, whereas an absorption of 4.6 mW per incident W is obtained without these elements enabling the confinement of the light beam. A factor of around 2.5 is obtained on the proportion of signal transmitted in the first chamber **106** thanks to the confinement means used. Furthermore, the widening of the second end **107** of the waveguide **104** has the other effect of reducing diaphony due to the fact that the second chamber **108** is not or is little illuminated by the light beam sent into the first chamber **106**.

The filling rate of the grooves in the diffraction grating **118** affects the decoupling realised. It is determined by simulation and is for example equal to around 50%.

According to an embodiment variant, the device **100** may comprise chambers **106** and **108** not having similar dimensions. In fact, given that the device **100** is a miniaturised device produced via the implementation of microelectronics techniques and MEMS/NEMS systems, a phase opposition may appear between the pressure signals measured in the two chambers **106** and **108** which is imperfect when the dimensions of the chambers **106** and **108** are identical. The subtraction of these two signals which is carried out to obtain the desired measurement is then not optimal. In order to improve this opposition of phases, it is possible that the widths and/or the lengths of the chambers **106** and **108** are different to each other. An optimisation by simulation (for example by resolving the equation of the pressure field in the device **100**, with chambers **106** and **108** of different sizes), for example via a calculation by the finite elements method, leads to the optimal ratio of the dimensions of the chambers **106** and **108**.

The curve represented in FIG. **4** corresponds to the amplitude of the signal obtained (in Pa, and corresponding to the difference in the pressures measured by the acoustic detectors in the two chambers **106** and **108**) as a function of the width of the second chamber **108** (in μm), for a first chamber **106** of width equal to around 300 μm. It may be seen in this figure that the maximum amplitude of the signal is not obtained for a second chamber **108** having a width similar to that of the first chamber **106**, that is to say equal to around 300 μm, but for a width greater than 300 μm in this particular case. In other cases, the maximum amplitude of the signal may be obtained for a second chamber **108** having a width less than that of the first chamber **106**.

The device **100** is for example formed by the assembly of three substrates:

- a first lower substrate comprising the acoustic detectors intended to be coupled to the chambers **106** and **108**, and in which are formed the inlet and outlet channels **114** and **116**,
- a second middle substrate in which are formed the light source **102**, the waveguide **104**, the diffraction grating **118** and the chambers **106** and **108**;
- a third upper substrate forming the cover of the chambers **106** and **108** and in which are also formed the capillaries **110** and **112**.

In a variant, the device **100** may be formed with only two substrates. In this case, the capillaries **114** and **116** are formed in the second substrate in which the chambers **106** and **108** are formed. The capillaries **114** and **116** may in this case have a height similar to that of the chambers **106** and **108**. By only resorting to two substrates instead of three, it is possible to reduce the thickness of the chambers **106** and **108** to a value less than around 300 μm on account of the fact that such a configuration with two substrates avoids the use of a middle substrate of which the thickness must correspond to the thickness of the chambers and which is difficult to handle when said thickness is less than around 300 μm. By etching the capillaries and the chambers in a same substrate with a depth which is less than the total thickness of the substrate (due to the fact that in this case, the upper walls of the chambers and the capillaries are formed by a non-etched part of the second substrate and not by a third substrate transferred onto the second middle substrate), it is possible to have chambers **106** and **108** of which the height is low while conserving a greater total thickness for the substrate enabling a handling of the substrate without risk of breakage. A device **100** formed with only two substrates enables the formation of chambers **106** and **108** of which the thickness is for example comprised between around 300 μm and 100 μm, but remains compatible with the formation of chambers **106** and **108** of thickness greater than around 300 μm.

This reduction in the thickness of the chambers **106** and **108** makes it possible to obtain an output signal of greater amplitude. Curve **10** represented in FIG. **5** corresponds to the amplitude of the signal obtained (in Pa, and corresponding to the difference in pressures measured by the acoustic detectors in the two chambers **106** and **108**) as a function of the distance between the capillaries **110** and **112** for a device **100** of which the chambers **106** and **108** have a thickness equal to around 300 μm, and curve **12** corresponds to the amplitude of the signal obtained for a device **100** of which the chambers **106** and **108** have a thickness equal to around 200 μm. FIG. **5** clearly illustrates the fact that the amplitude of the signal represented by curve **12** is greater than that obtained for the signal represented by curve **10**. Furthermore, the amplitude of the output signal is impacted by the distance between the capillaries **110** and **112** on account of the energy losses in the limit layers and the particular form of the flow of the gas.

An example of method of producing the photoacoustic detection device **100** is described in relation to FIGS. **6**A to **6**I which represent schematic sectional views of the elements of the device **100**. In this embodiment example, the device **100** is formed via an assembly of three substrates.

FIGS. **6**A to **6**F represent the steps relating to the formation of the second middle substrate which comprises the waveguide **104**, the diffraction grating **118** and the chambers **106** and **108**, as well as other elements such as electrical contacts of the acoustic detectors. FIGS. **6**G to **6**I represent the later steps of the method during which the second middle substrate is made integral with the first lower substrate and with the third upper substrate forming especially the cover of the chambers **106** and **108**.

As represented in FIG. **6**A, the second middle substrate corresponds to a bulk semi-conductor substrate **134**, here silicon-based. The material at an upper face of the substrate **134** corresponds to the material which will form the upper cladding layer **128** of the waveguide **104**. Then a first deposition or an epitaxial growth is carried out of a layer **136** comprising a material with refractive index greater than that of the material of the substrate **134** and transparent to the wavelength(s) intended to be transmitted by the waveguide **104**, here a material transparent in the infrared and for wavelengths comprised between around 3 μm and 10 μm. A part of this layer **136**, for example formed by epitaxy, is intended to form the core layer **126** of the waveguide **104**. The thickness and the material of the layer **136** are chosen so that the waveguide **104** can carry out a single-mode guiding of the light beam.

The thickness of the layer **136** is for example comprised between around 1 and 10 μm, and is for example germanium-based or SiGe-based depending on the material desired to form the core layer **126** of the waveguide **104**. In the case of a SiGe-based layer **136**, the germanium composition of the SiGe, that is to say the proportion of germanium in the SiGe, may be constant or instead vary throughout the thickness of the layer **136** to form a core layer comprising an index gradient according to a profile (in the direction of the thickness of the layer **136**) being able to be triangular or trapezoidal. For example, for a waveguide **104** intended to transmit a wavelength of 4.5 μm, the germanium composition within the layer **136** may form, throughout the thickness of this layer, a triangular profile over a thickness of around 3 μm with a germanium composition extending from 0% (at the upper and lower faces of the layer **136**) to 40% in the middle of the layer **136**, these variations being for example linear throughout the thickness of the layer **136**. In a variant, the layer **136** may be SiGe-based and comprise a constant germanium concentration throughout the thickness of this layer and for example equal to 40%, the layer **136** having in this case a thickness for example equal to 2.7 μm.

The diffraction grating **118** is then formed at the upper face of the layer **136**. To achieve this, a lithography and an RIE (reactive ion etching) or DRIE (deep reactive ion etching) type etching are implemented at the place provided for the diffraction grating **118**, that is to say at the part of the second end **107** of the waveguide **104** that is intended to be located near to the place provided for the first chamber **106** which is intended to receive the light beam. The photolithography and the etching are implemented such that they form, in a part of the thickness of the layer **136** (the thickness of the layer **136** being for example comprised between around 1 μm and 10 μm), the grooves of the diffraction grating of which the dimensions and the spacing correspond to the calculated values in order to obtain the desired diffraction angle, as described previously.

After this etching, a layer **138** of material of which the refractive index is less than that of the material of the layer **136**, such as SiO_2, SiN or Si_3N_4, is formed, for example by deposition, on the layer **136** and in the patterns etched through the upper face of the layer **136** to form the diffraction grating **118** (FIG. **6**B).

The layer **138** is then planarized, for example via chemical-mechanical planarization (CMP) with stoppage on the upper face of the layer **136**, in order that the low index material is only conserved in the patterns of the diffraction grating **118**.

The core of the waveguide **104** is then formed by lithography and etching of the layer **136** in order that at least one part of the remaining portions of the layer **136** form the core layer **126** of the waveguide **104**. This etching is not visible in FIGS. **6**A-**6**I. This etching is carried out through a part or the totality of the thickness of the layer **136** depending on the structure desired to form the core of the waveguide **104**. When the waveguide **104** comprises a core layer **126** made of SiGe with triangular shaped index gradient, the layer **136** may be etched such that the remaining portion forming the waveguide **104** has a width equal to around 3.3 μm, or comprised between around 3.3 μm and 8 μm, which allows it to carry out a single-mode guiding of a light beam of wavelength equal to 4.5 μm. As described previously, the second end **107** of the waveguide **104** is formed with progressive widening in order to enable a transmission of the fundamental mode of the light beam for which the diffraction grating **118** is optimised while reducing the diffraction of the beam along the direction of the widening, and thus improving the horizontal confinement of the light beam.

The remaining portion(s) of the layer **136** are then covered by the deposition or the epitaxial growth of a layer **140** intended to form the lower cladding layer **124** of the waveguide **104**, which thus comprises a material of lower refractive index than that of the core layer, and for example silicon-based in the case of a core layer made of SiGe. This layer **140** is then planarized for example via CMP in order that the upper face of the layer **104** forms a flat surface (FIG. **6**C).

In a variant, the formation of the diffraction grating **118** could be simplified by implementing a single lithography step, a single etching step and a single CMP step.

Materials other than silicon and germanium may be used to form the waveguide **104**, said materials having nevertheless to enable a transmission of the wavelength of the light beam and be compatible with the techniques implemented to form the device **100**. It is nevertheless possible to form the waveguide **104** with a core layer made of silicon and arranged between two cladding layers made of SiN.

A dielectric layer **142** is then deposited on the layer **140**, for example SiO_2-based and of thickness equal to around 1 μm, or SiN-based or Al_2O_3-based. Said dielectric layer **142** is etched at emplacements intended to form electrical contacts pick-up of the acoustic detectors of the device **100** (FIG. **6**D). An electrically conducting layer, for example metal-based, is then deposited on the dielectric layer **142**. This electrically conducting layer is for example AlSi-based (comprising around 1% of silicon). The electrically conducting layer is then etched in order that the remaining portions **144** of this layer, filling especially the places previously etched in the dielectric layer **142**, form the electrical contacts of the acoustic detectors. At least one other remaining portion **146** of this electrically conducting layer may also be conserved in order to form the lower reflective layer **120**, especially when the material of the dielectric layer **142** does not allow that this reflection function of the light diffracted by the diffraction grating **118** is fulfilled with the layer **142** (FIG. **6**E). In the case of a layer **142** made of SiO_2 and a core of the waveguide **104** made of germanium or made of SiGe surrounded with cladding layers made of silicon, this luminous reflection function is fulfilled with the layer **142** because a total luminous reflection takes place at the Si/SiO_2 interface due to the small angle of incidence of the light beam diffracted by the diffraction grating **118**.

Another dielectric layer **147**, for example comprising a material similar to that of the dielectric layer **142**, and/or of thickness similar to that of the dielectric layer **142**, is then deposited while covering the remaining portions **144**, **146**. A sealing layer is then formed in order to enable thereafter the second middle substrate to be made integral with the first substrate comprising the acoustic detectors. This sealing layer may correspond either to a metal layer, for example a gold-based layer of thickness equal to around 800 nm, or an aluminium-based layer of thickness equal to around 400 nm arranged on a layer of germanium of thickness equal to around 200 nm, making it possible to achieve a eutectic sealing with the semi-conductor (for example silicon) of the first substrate. Said sealing layer may also correspond to a layer of polymer for example of thickness equal to around 1 μm. As represented in FIG. **6**F, said sealing layer is etched in order to only conserve sealing portions **148** at some spots. Furthermore, some remaining sealing portions are electrically connected to the remaining conductive portions **144** in order to form electrical contacts which will be electrically connected to the acoustic detectors of the device **100**.

As represented in FIG. **6**G, the second middle substrate **150** obtained by the implementation of the steps described previously is turned over and made integral with the first substrate, referenced **152**, which comprises the acoustic detectors as well as other electrical and/or electronic elements not visible in FIGS. **6**A-**6**I. Due to the turning over of the second middle substrate **150**, the diffraction grating **118** is localised in the lower part of the core layer **126** of the waveguide **104**, as described previously with reference to FIG. **3**. The acoustic detectors **154**, which are beam type piezoresistive microphones, are arranged near to the part of the second substrate **150** in which the chambers **106** and **108** are intended to be formed, and are electrically connected to the electrical contacts **144** formed previously. Furthermore, the detectors **154** are arranged in an etched part **156** of the first substrate **152** which will make it possible later to expose the detectors **154** to air in order that they are subjected to atmospheric pressure. Furthermore, the detectors **154** are connected to strain nanogauges **158** enabling the transformation of the pressures measured by the acoustic detectors **154** into electrical signals.

After sealing the second middle substrate **150** to the first substrate **152**, the second middle substrate **150** may be thinned to the desired thickness corresponding to the desired height of the chambers **106** and **108**, for example equal to 300 μm (FIG. **6**H). This thinning is carried out by reducing the thickness of the bulk layer **134**.

Steps of lithography and etching (for example of DRIE type) are then carried out through the second middle substrate **150** to form the chambers **106** and **108**.

The light of the laser light source **102** may be injected directly into the waveguide **104**, the light source **102** being in this case coupled end-to-end with the waveguide **104** via a so-called “hybrid” coupling. It is also possible to have a “heterogeneous” coupling in which the laser light source **102**, for example of QCL type and made of III-V material, is transferred onto the silicon substrate. An additional structure, formed for example by lithography and etching, assures in this case the coupling between the waveguide **104** and the light source **102**. The epitaxied layers of the QCL laser may be transferred onto silicon by direct bonding, as described for example in the document “Electrically driven hybrid Si/III-V Fabry-Perot lasers based on adiabatic mode transformers” of B. Ban Bakir et al., Opt. Express 2011, vol. 19, no 11, 23 May 2011.

As represented in FIG. **6**I, the third upper substrate **160** is made integral on the thinned second middle substrate **150**. The capillaries **110** and **112** are formed in the third upper substrate **160** prior to making this third substrate **160** integral with the second middle substrate **150**. The making integral is implemented via a eutectic sealing layer, for example formed of a stack of a layer of tungsten of thickness equal to 50 nm, of a layer of tungsten nitride of thickness equal to 50 nm and a layer of gold of thickness equal to 800 nm, deposited then structured in the form of a sealing bead **162**. The third substrate **160** forms especially the upper walls of the chambers **106** and **108**. Thus, one of the remaining portions of the sealing layer may be used to form the upper reflective layer **122** in the first chamber **106**. The eutectic sealing is carried out between the gold layer of the sealing bead **162** and the silicon (corresponding to the material of the thinned layer **134**) of the second middle substrate **150**.

In a variant, prior to making the third substrate **160** integral with the second substrate **150**, the capillaries **110**, **112** may be formed after the deposition and the structuring of the eutectic sealing layer. In this case, the upper reflective layer **122** is deposited later for example through a stencil so as to localise this layer at the part of the third upper substrate **160** intended to form the upper wall of the first chamber **106**.

The inlet **114** and outlet **116** channels are formed through the first lower substrate **152**. Other openings **164** are formed through the first lower substrate **152** especially so that the acoustic detectors **154** are at atmospheric pressure and form accesses for etching portions of temporary dielectric material present in the substrates, in contact especially with the acoustic detectors **154** and with the metal portions **144**, **146**.

In the case of the formation of the device **100** with only two substrates, the capillaries **110** and **112** are formed in the same layer as the chambers **106** and **108**, that is to say in the second substrate **150**. In this case, the upper reflective layer is formed via a step of metallisation with a stencil at the bottom wall of the cavity intended to form the first chamber **106**, prior to the two substrates being made integral.

In the device **100** described previously, the diffraction grating **118** is dimensioned especially as a function of the wavelength of the light beam intended to be diffracted, the wavelength of the light beam being adapted as a function of the nature of the gas to be detected. The device **100** may be adapted to carry out a detection of several types of gas by forming in the device **100** several parallel waveguides which emerge on one or on two inlet faces (on each side) of the first chamber **106**, each of the waveguides being coupled to a light source emitting at a different wavelength, for example between 4 μm and 5 μm, which is intended to be diffracted by the diffraction grating formed on each of the waveguides. An optical multiplexer may also be used so that the chamber **106** can receive different wavelengths, as described in the document EP 2 515 096 A1. Moreover, it is also possible that the two chambers **106** and **108** are coupled to light sources emitting for example at wavelengths different to each other, which makes it possible to excite the gas present in one or the other of the chambers **106** and **108** depending on the gas to be detected.

In the device **100** described previously, the horizontal confinement of the light beam is achieved thanks to the widening of the second end **107** of the waveguide **104**. This horizontal confinement may be improved by forming trenches filled with a reflective material, for example a metal such as gold, aluminium, around the first chamber **106**. These trenches are sufficiently far away, for example several tens of microns, from the first chamber **106** so as not to add to the thermal background noise, linked to the absorption of infrared radiation by the materials surrounding the excited chamber. Such trenches may be formed in the second substrate **150**, for example during the etching of the chambers **106** and **108**.

In the example of FIG. **1** described previously, the inlet **114** and outlet **116** channels are connected to the capillaries **110** and **112** substantially at the level of the middle of said capillaries **110**, **112**. In a variant, given that the device **100** is a miniaturised device formed by the implementation of microelectronic steps, said inlet **114** and outlet **116** channels may be connected to the capillaries **110** and **112** at a level other than their middle, and without perturbing the symmetry of the flow of gas in the device **100**.

To increase the intensity of the signal measured by the acoustic detectors of the device **100**, it is possible to place the capillaries **110**, **112** at the ends of the chambers **106**, **108**. Such a configuration makes it possible to increase by around 5% the amplitude of the signal measured by the acoustic detectors.

The different embodiment options described in the document EP 2 515 096 A1, such as for example the use of a Peltier effect cooler, an amplifier integrated into the photoacoustic detection device, or the different examples of materials described, may apply to the photoacoustic detection device of the invention.

The invention claimed is:

1. A microelectronic photoacoustic detection device comprising

at least one substrate comprising cavities forming a Helmholtz type differential acoustic resonator;

acoustic detectors coupled to two of said cavities forming chambers of the resonator;

a light source capable of emitting a light beam at at least one given wavelength;

an optical waveguide comprising a first end optically coupled to the light source and a second end optically coupled to a first of the two chambers;

in which the second end comprises, at an interface with the first chamber, a width of value greater than that of the width of the first end and greater than that of said at least one given wavelength, and/or in which the photoacoustic detection device comprises at least one diffraction grating arranged in the second end of the waveguide and capable of diffracting a first part of the light beam towards a lower reflective layer arranged under the second end and a second part of the light beam towards an upper reflective layer arranged at an upper wall of the first chamber.

2. Device according to claim **1**, in which the ratio between the width of the second end at the interface with the first chamber and the width of the first end is greater than or equal to 3.

3. Device according to claim **1**, in which the second end forms a portion of the waveguide of which the width increases from a first value equal to that of the width of the first end up to a second value equal to that of the width of the second end at the interface with the first chamber.

4. Device according to claim **3**, in which the width of the second end increases on a part, called first part, of the second end of which the length is greater than or equal to around ten times the width of the second end at the interface with the first chamber.

5. Device according to claim **1**, in which the diffraction grating is arranged in a part, called second part, of the second end of which the width is substantially constant and equal to that at the interface with the first chamber.

6. Device according to claim **1**, in which the diffraction grating is arranged at an interface between a core layer of the waveguide and a lower cladding layer of the waveguide, the lower cladding layer being arranged between the core layer and the lower reflective layer.

7. Device according to claim **1**, in which the diffraction grating is capable of diffracting the light beam such that the first or the second part of the light beam reaches, after a reflection on the lower reflective layer and/or the upper reflective layer, a bottom wall of the first chamber which is opposite to that in contact with the second end of the waveguide.

8. Device according to claim **1**, in which the acoustic detectors are arranged in a first substrate and coupled to the chambers of the resonator formed in a second substrate made integral with the first substrate, volumes of the chambers communicating together via capillaries formed in a third substrate made integral with the second substrate.

9. Device according to claim **1**, in which the acoustic detectors are arranged in a first substrate and coupled to the chambers of the resonator formed in a second substrate made integral with the first substrate, volumes of the chambers communicating together via capillaries formed in the second substrate, the second substrate having a thickness less than 300 μm.

10. Device according to claim **1**, further comprising trenches filled with at least one optically reflective material and arranged around the first chamber.

11. Device according to claim **1**, in which the two chambers comprise dimensions different to each other.

12. Device according to claim **1**, in which the acoustic detectors comprise beam type piezoresistive microphones.

13. A gas detection device, comprising at least one microelectronic photoacoustic detection device according to claim **1** and further comprising gas inlet and outlet channels communicating with the chambers of the resonator and in which the wavelength intended to be emitted by the light source corresponds to an absorption wavelength of a gas intended to be detected.

14. A method of producing a microelectronic photoacoustic detection device, comprising at least the steps of:

forming, in at least one substrate, an optical waveguide comprising a first end and a second end,

forming a light source capable of emitting a light beam at at least one given wavelength and such that the light source is optically coupled to the first end of the waveguide,

forming, in said at least one substrate, cavities forming a Helmholtz type differential acoustic resonator, two of said cavities forming chambers of the resonator such that a first of the two chambers is optically coupled with the second end of the waveguide,

coupling of the acoustic detectors with the chambers of the resonator,

in which the second end comprises, at an interface with the first chamber, a width of value greater than that of the width of the first end and greater than that of said at least one given wavelength, and/or in which the method comprises the formation of at least one diffraction grating in the second end of the waveguide capable of diffracting a first part of the light beam towards a lower reflective layer arranged under the second end and a second part of the light beam towards an upper reflective layer arranged at an upper wall of the first chamber.

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